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CRYOGENIC METALLIC POSITIVE EXPULSION BELLOWS EVALUATION

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D.T. Covington and R.F. Fearn

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS3-12017

MARTIN MARIETTA CORPORATION

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FINAL REPORT

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SUMMARY

This report describes the work performed in accordance with NASA-Lewis Research Center contract NAS3-12017 to evaluate a metallic positive expulsion bellows in liquid hydrogen. The bellows assembly was designed and fabricated by SOLAR, a Division of International Harvester, and was government-furnished to MMC (Martin Marietta Corporation) for test. A spare bellows was provided in the event the original one should fail prematurely.

The testing was accomplished in two parts; an expulsion efficiency test using water as the test fluid, and a series of cycle and leak tests in liquid hydrogen. The expulsion efficiency test was performed on a test bench with the bellows assembly in the inverted position. The expulsion efficiency (ratio of the quantity of fluid expelled to that required to fill the device) was found to be 98.4% (the average of several tests).

The liquid hydrogen cycle tests were preceded by a series of liquid nitrogen and hydrogen check-out tests to verify the integrity of the apparatus and the operating procedures. During the course of these checkouts it was observed that the bellows had failed (developed a leak in excess of 10^{-6} standard cubic centimeters of helium gas/sec). Consequently it was necessary to replace the original bellows with the spare bellows in order to accomplish the LH_2 cycle tests.

The LH_2 cycle tests were performed in groups of 10 cycles each (20 reversals), followed by a leak check of the bellows while the system was cold. In addition, a "warm" leak check was ordinarily performed after each 20 cycles after the bellows assembly had been removed from the cryostat. Following the fifth group of cycles (100 reversals) a leak was detected (2×10^{-5} scc He/sec) in the spare bellows in excess of the allowable value, thereby terminating the program as defined in the original contract. Subsequently, however, a supplemental agreement was negotiated between NASA and MMC, and 20 additional cycle tests were conducted. These resulted in no further increase in the leak rate.

A failure analysis of the bellows performed by SOLAR correlated the leaks with regions of corrosion found within the bellows. These are believed to be the result of inadequate cleaning procedures, and/or the use of tap water in some of the test operations. These deficiencies can easily be overcome in the future. In addition, a redesign of the weld joint between the bellows sleeve and the end domes of the assembly appears desirable to eliminate a crevice that exists in the current design.

This report describes in considerable detail all the apparatus employed in the tests, as well as the test operations and procedures. The specific results of the failure analysis are also included in order that all data pertinent to the performance of the bellows are contained in a single document.

INTRODUCTION

In order to assure the delivery of liquid propellants from flight vehicle propellant tanks to the rocket engine(s), some type of positive expulsion device is often required. This is particularly true in a low-g environment where the liquid and vapor phases tend to be intermixed.

Many different types of devices have been proposed for positive expulsion systems and some have been developed to a fairly high degree of perfection in recent years. Probably the most common class of these devices is the flexible membrane which may take the form of bladders, diaphragms, bellows, or some combination of these three. These devices are relatively simple and cheap, are light weight, have high expulsion efficiencies, and do not have sliding surfaces that are subject to wear and leakage.

The choice to be made among the three basic types of devices is largely dependent upon the specific application. The bellows is generally heavier than the other two devices, and it can not be readily adapted to a wide variety of configurations. On the other hand, it can be designed so that the bellows membrane material is not highly stressed, with the attendant benefit of a long (cycle) life.

In general these devices may be fabricated from either metals or non-metals. The metals offer advantages with regard to impermeability, chemical compatibility and operational temperature range for containment of exotic propellants. The non-metals are generally more flexible, a very important consideration for bladders and diaphragms, but they tend to be somewhat permeable, and have somewhat limited compatibility with many propellants.

The program described in this report was conducted to evaluate one particular device offering considerable promise for many applications, i.e., the metallic bellows. The application of primary interest is the expulsion of cryogenics, specifically liquid hydrogen. The selection of stainless steel for construction of the bellows results in a device that is completely compatible with the liquid hydrogen environment, and one that can be readily fabricated with leak tight joints.

The bellows assembly that was tested was designed and fabricated by SOLAR, a division of International Harvester, under contract to NASA Lewis Research Center. It was not designed for a specific vehicle application, but rather to demonstrate the technology; i.e., the capability to produce a metallic bellows suitable for service in liquid hydrogen. The primary goal was to achieve a minimum of 100 complete cycles in liquid hydrogen without failure; i.e., without developing a leak in excess of 10^{-6} Scc He/sec. A second objective was to demonstrate a high expulsion efficiency; i.e., an efficiency of at least 97.5%. The specific program that was conducted in response to these objectives, and the results obtained, are described in the sections following.

EXPULSION EFFICIENCY TESTS

The first testing of the bellows assembly to be accomplished by MMC was for the purpose of determining the expulsion efficiency of the assembly and also its spring characteristics; i.e., its linear displacement as a function of applied pressure (or vacuum). This phase of the testing was accomplished early in August immediately following receipt of the bellows assembly and spare bellows from SOLAR. A description of this test effort is presented in the following paragraphs.

APPARATUS

Bellows Assembly - The bellows assembly that was tested consists of three major components: a pressurization gas storage vessel, an outer tank section which is pressurized to expell the liquid and the inner bellows section which contains the liquid. The bellows assembly is shown ready for test in the inverted position in Figure 1. A cross-section of the assembly is shown in Figure 2, a layout drawing of the apparatus used for the LH_2 cycle tests. A detailed description of the assembly is contained in SOLAR Report RDR-1619, "Production Evaluation Test Report for Expulsion Bellows-Tank Assembly," August 6, 1968.

The inner bellows section consists of two thin walled domes, joined by a single ply, zero radius convoluted bellows as shown in Figure 3. A spare inner section was provided for use in the event the one originally installed in the assembly should fail.

The operation of the assembly is very simple. The bellows is filled with liquid under pressure through the outlet port until the inverted top dome of the bellows seats firmly against the dome of the pressure vessel. Expulsion is then effected by admitting cooled helium gas through the inlet port and into the outer tank section. This compresses the bellows and expells the liquid through the outlet port until the bellows top dome firmly seats against the bottom dome of the outer tank. The bellows is approximately 13½" (.343 meters) in diameter, and the dome travels 5¼" (.133 meters) from the extended to the compressed position to expell slightly more than 3 gallons (.0113 $meters^3$) of liquid.

Test Equipment - The apparatus used for the expulsion efficiency tests is shown in Figure 1. It consists primarily of a "K" bottle and a vacuum pump to provide the desired differential pressure across the bellows, a glass graduate and scales to measure the quantity of water added to and expelled from the bellows, and miscellaneous valves, regulators, hose, tubing and fittings.

Nitrogen was used as the pressurization gas and was obtained from a standard 'K' bottle through a 2-stage regulator. It is water-pumped and has a purity of 99.991%. The vacuum pump used is a Welch Manufacturing Company, Duo-seal Type 1403, capable of attaining a vacuum of 1 mm Hg (133 newtons/meter^2). The scales used to weigh the water (deionized) were manufactured by Ohaus Company and have a triple beam providing a sensitivity of 0.001 Kilograms. A 1000 milliliter (0.001 meters^3) graduated flask was used to obtain a volumetric measurement of the water. A J. P. Marsh Company compound gage capable of reading 30" Hg vacuum (0 kilo-newtons/meters^2) and 15 psig pressure (185 kilo-newtons/meter^2) was used to monitor the applied pressure. A Veeco type FR, Bellows seal valve was installed between the pressure source and the bellow assembly for precise control of applied pressure. The equipment was mounted as shown for easy accessibility.

TEST OPERATIONS

Upon the receipt from SOLAR, the bellows assembly and the spare bellows were visually inspected for evidence of damage during shipment. None was apparent, so the bellows assembly was readied for testing.

The spring rate of the bellows was determined by applying a predetermined pressure to the bellows and then determining the resultant position of the bellows dome by means of a calibrated rod inserted through the outlet port. The relaxed position (zero differential pressure) was determined first, then both positive and negative pressures were applied. The bellows was pressurized in 1 psi (6890 newtons/meter^2) increments to a maximum value of 10 psig (150 kilo-newtons/meter^2). Then the pressure was vented, and a controlled vacuum was applied in increments of 1" Hg (3380 newtons/meter^2) to a maximum value of 10" Hg (47.6 kilo-newtons/meters^2). In the fully extended position the bellows can be damaged by application of an excessive differential pressure, so the vacuum hand valve was very carefully controlled to assure that the [illegible] did not exceed 5 psi (33.4 kilo-newtons/meter^2). The test was repeated to confirm the measurements, and the results are plotted in Figure 4.

The expulsion efficiency test was performed to determine the volumetric efficiency of the bellows assembly; i.e., the ratio of the quantity of liquid expelled from the assembly to that initially contained in it. The test was performed with the assembly in the inverted position as shown in Figure 1. Since the bellows is neither fully extended nor compressed in the relaxed position, the vacuum pump was used to apply a 5 psi (33.4 kilo-newtons/meter^2) differential pressure to fully extend it. Then with the outflow line disconnected, the bellows was filled to the inlet opening of the outflow line with deionized water at ambient temperature, using the glass graduate to obtain an accurate measure of the volume added. To provide comparative data, the water was also weighed, but the weight measurement is not of the same degree of accuracy as the volume measurement. The outflow line was then attached and filled with water to the end of the outflow tube.

The water was expelled from the bellows by application of 20 psig (219 kilo-newtons/meter^2) to the pressurization side of the bellows. The outflow was collected in the glass container shown in Figure 1 and weighed. Finally, the outflow volume was measured with the graduate and the expulsion efficiency calculated.

The bellows was dried by means of a nitrogen gas purge and placed in a drying oven overnight prior to conducting a second expulsion efficiency test. The results of the tests are presented in Table I. Subsequently, two additional tests were conducted, but this time the bellows was exercised (filled and expelled) several times before making the measurements. The results of these tests are also presented in Table I.

RESULTS

It should be noted that a higher expulsion efficiency was obtained on the first expulsion cycle after filling the bellows, than on subsequent cycles. It is believed that this discrepancy is the result of a small amount of air being trapped within the bellows convolutions during the first filling with water, and that the lower efficiency obtained from the last two tests is more representative of that to be expected from an operational system. It is not obvious, however, why air trapped within the bellows should produce the effect noted.

The expulsion efficiency is also to some degree a function of the differential pressure applied to the bellows in the extended and compressed positions. From the data plotted in Figure 4, it is evident that the expulsion efficiency will be reduced if the initial Δp following the fill operation is less then $\sim 1\frac{1}{2}$ psi (10.3 kilo-newtons/meter^2) in the outward direction, or less than ~ 6 psi (41.3 kilo-newtons/meter^2) in the inward direction during expulsion. Since all the expulsion efficiency data were taken at differential pressures greater than these values, this should have had no effect on the results.

CYCLE/LEAK TESTS

During the period from the initiation of the contract (28 June 1968) until approximately mid-September, work proceeded on the design, procurement, fabrication and assembly of the test apparatus to be used in the LH_2 cycle/leak tests of the bellows assembly. The first checkout of the apparatus was conducted on 17 September using LN_2. Some difficulties with the apparatus were encountered, and as a result, several modifications were incorporated. Also, the bellows was found to leak excessively, so the spare bellows was installed for the final cycle tests.

The checkouts were successfully completed early in October, and a series of 50 cycles of the bellows with LH_2 was completed on 15 October. At this point, the bellows leak rate exceeded the maximum allowable value, thereby marking completion of the program as originally planned. Subsequently, however, the bellows was subjected to an additional 20 cycles to determine whether the leak would get progressively worse. The final cycles were conducted on 12 November.

A detailed description of the program is presented in the following paragraphs.

CYCLE TEST APPARATUS

The apparatus used in the cycle/leak tests consisted of 5 major items as follows: (a) a cryostat which housed the bellows assembly and associated equipment, (b) a liquid nitrogen heat exchanger which precooled the helium pressurization gas, (c) a control console which was used to control and monitor test operations, (d) a CEC leak detector, and (e) miscellaneous support equipment such as dewars and vacuum pumps. A schematic of the system is shown in Figure 5; a photograph of the equipment installed in the test cell at the PRL (Propulsion Research Laboratory) is shown in Figure 6.

Cryostat Assembly - A layout drawing of the cryostat assembly is shown in Figure 2. The drawing shows the bellows assembly installed inside the cryostat, as well as the associated plumbing and instrumentation. A photograph of the apparatus is shown in Figure 7.

A primary consideration in the design of the apparatus was simplicity of assembly and test. In addition to providing the temperature environment required for testing the bellows assembly, the LH_2 contained in the cryostat also serves as the refrigerant to cool the helium pressurization gas used for expulsion, the reservoir from which the bellows is filled, and the sink into which the outflow from the bellows is expelled.

Cryostat pressurization for filling the bellows is accomplished with a small electrical ullage heater; outflow is controlled (and measured) by means of an orifice in the expulsion line from the bellows. Consequently, only 3 pressure measurements (cryostat, helium pressurization, and orifice inlet) are required to monitor and control the entire fill/expulsion cycle.

The cryostat, shown on the left in Figure 7, is an open-mouth dewar, Type DF344 manufactured by Standard Air. It is a vacuum jacketed stainless steel vessel approximately 19 inches (0.482 meters) OD, 17 inches (0.432 meters) ID, and 40 inches (1.016 meters) deep, and has a capacity of 150 liters (0.150 meter^3). It had been used successfully in a number of different programs over a period of nearly ten years, but failed early in this program as a result of leakage through the lead seal at the top surface. An attempt was made to seal the surface with epoxy, but this also failed. Finally a satisfactory repair was effected by replacing the lead seal with a machined stainless steel face welded to the inner and outer shells of the cryostat.

The lid of the cryostat is constructed of stainless steel with Heliarc welded joints. It is pearlite filled and evacuated. All penetrations through the lid are either "O" ring sealed, or use a copper crush seal. Three small rods attached to the lid support the bellows assembly at the desired level inside the cryostat.

To insure that the pressurizing gas for the bellows was conditioned to the desired temperature, a heat exchanger consisting of 34 feet (10.4 meters) of 3/8 inch (0.00955 meters) OD copper tubing was coiled to fit inside the cryostat above the bellows assembly as shown. It was sized to reduce the ΔT between the pressurizing gas and the LH_2 to less than 3°K, using a conventional Nusselt equation for turbulent flow. Liquid level sensors were provided to assure that the heat exchanger remained submerged in the cryogen.

Initially the pressurization gas storage vessel was vented directly into the cryostat through a small vent tube so that it would be exposed to the same pressure and temperature fluctuations as the cryostat. In early checkout tests, however, it was observed that the pumpdown of the cryostat was exceedingly slow, and it was concluded that the difficulty was the result of condensation inside the storage vessel. Evaporation from the vessel probably would be very slow because there is no provision for directly heating the vessel. To overcome this difficulty, the original vent line (shown dashed in Figure 2) was removed and replaced by a line that connects into the helium pressurization line as shown in Figure 2. This resulted in simultaneous pressurization (and venting) of the pressure vessel and the bellows and an attendant increase in helium consumption, but it did isolate the vessel from the cryostat and thereby reduce the pumpdown time.

The square-edge orifice used to maintain the desired flow rate at the normal expulsion pressure consists of a standard AN tube cap with a drilled hole 0.013 inches (0.00033 meters) in diameter. It was designed for a flowrate of 5 gpm(56×10^{-6} meters^3/sec) at an expulsion pressure of 20 psig (219 kilo-newtons/meter^2) although lower pressures, and consequently lower flowrates, were used in many of the tests.

In addition to the 800 watt heater located in the ullage volume to pressurize the cryostat, a second heater of 200 watts capacity is located at the bottom of the cryostat to assist in vaporizing any hydrogen that remains in the cryostat after draining.

Liquid Nitrogen Heat Exchanger - To temperature condition the bellows pressurizing gas before it enters the cryostat, a liquid nitrogen heat exchanger was installed in the pressurization line upstream of the cryostat. It consists of a coil of 50 feet (15.24 meters) of 3/4 inch (0.019 meters) OD copper tubing immersed in LN_2 inside a 30 inch (0.762 meters) diameter foam-insulated container. It was sized to reduce the temperature of the helium gas from ambient to approximately 80°K before entering the cryostat.

Control Console - Usually tests involving the use of liquid hydrogen are controlled from a console located in the Control Center at PRL. For this particular program, however, the console was located adjacent to the cryostat in the test cell. This method of operation provided precise control of the test without the need from remotely operated valves, and because of the relatively safe nature of the test, did not expose the operating personnel to undue hazards. Figure 8 is a closeup view of the console panel; Figure 6 shows it installed in the test cell with the other test apparatus.

The main components of the console are the valves and associated gages necessary to control and monitor the bellows fill and expulsion sequences once the cryostat has been filled. The bellows and cryostat inlet valves are Hoke Globe valves, Type RB 272 with brass bodies. The cryostat vent valve is a Powell Globe valve, modified with an extended stem for low temperature service. The gages used are conventional Bourdon gages, having ranges appropriate for the measurements being made.

To avoid contamination when removing the bellows assembly from the cryostat, and to minimize the pump down time during the leak check operation, vacuum valves (Hoke Bellows Seal, Type TY 445L, Seal Welded) were placed between the console and the cryostat in the orifice pressure line and in the bellows inlet line.

Leak Detector - Helium leakage through the bellows was measured by means of a Consolidated Electrodynamics Corporation leak detector, Type 24-120A. It is a simplified mass spectrometer sensitive to minute traces of helium. It operates at a pressure level of 2×10^{-4} mm Hg (0.0266 newtons/meter^2) using a self-contained vacuum system consisting of a small

21 liter/min (0.00035 $meter^3$/sec) roughing pump, oil fractionating diffusion pump, liquid nitrogen cold trap, and associated valving.

The leak detector was used both to measure an unknown leak rate and to locate or pinpoint a leak. To quantitatively measure an unknown leak rate it is first necessary to calibrate the detector with a self-contained "calibrated leak." This provides a known leakage of helium into the system and permits accurate measurement of leak detector "sensitivity," the quantity of helium that deflects the output meter one division. The detector is capable of measuring leak rates over a range of five orders-of-magnitude down to a minimum value of 3×10^{-10} Scc He/sec.

Support Equipment - The support equipment required for the tests included the cryogenic liquid supply vessels (dewars) gaseous nitrogen, hydrogen and helium supplies, two vacuum pumps, and miscellaneous valves and interconnecting piping. The helium was supplied from regulated high pressure cylinders, while the facility system supplied the nitrogen gas. Hydrogen gas for purging was obtained directly from the ullage of the liquid hydrogen dewar. Liquid hydrogen was supplied from a company-owned Linde LSH-1000, double walled, vacuum-insulated dewar. It is a mobile unit having a capacity of 1000 liters (1.0 $meter^3$) and an operating pressure range of 0 to 150 psig (1134 kilo-newtons/$meter^2$). Liquid nitrogen was supplied from a Ronan & Kunzel vacuum and powder insulated mobile dewar. It has a capacity of 600 gallons (2.27 $meter^3$), and is capable of operating at pressures to 200 psig (1480 kilo-newtons/$meter^2$).

A Kinney, KS-47 vacuum pump was used for purging and rough pumping, and a portable high vacuum unit was used for pumping the cryostat down to the leak check pressure range of 10^{-4} mm Hg (0.0133 newtons/$meter^2$). This unit includes a CENCO HY-VAC 14 rough pump or fore pump, an NRC diffusion pump, and the associated vacuum gages.

INSTRUMENTATION

The specific measurements that were provided for evaluation of the bellows assembly are shown in Table II. These include the following: liquid hydrogen temperature, helium gas temperature and pressure, cryostat pressure, metering orifice upstream pressure, liquid hydrogen level in the cryostat, and heater power. The locations of sensors are shown in Figure 2.

The pressure and temperature measurements were recorded on Bristol strip chart recorders located in the Control Center (Figure 9), using the basic instrumentation system installed at FRL. This system was designed to accurately handle the requirements of a variety of test programs to be conducted in the test cells. All data channels are brought into the Control Center patch system, which provides maximum flexibility of equipment selection. Time correlation of the 6 recorded measurements was provided by a central timing device. To obtain the system accuracies indicated in Table II, the instrumentation was calibrated in accordance with the procedure detailed in Appendix A.

The two point level sensors located in the cryostat were connected to a Cryogenics Research Model LP-10R Liquid Level Indicator that provides a visual readout. A small change in the sensor temperature as the sensor moves from the gas to the liquid phase (and vice versa) results in a color change in the indicator lights located on the display panel.

Power to the two electrical heaters was supplied from a Superior Electric Company Powerstat that was adjusted to provide the desired power input. A Sensitive Research Instrument Corporation Model DWEW wattmeter was used to measure the power provided to each heater.

SYSTEM CHECKOUTS

Cryostat Leak Check - Prior to installation of the cryostat in the test cell, a leak check of the entire cryostat assembly (including the bellows) was attempted. The cryostat was connected to the vacuum bench pumping system, but it was not possible to achieve a sufficiently high vacuum to perform a quantitative leak check. The bellows assembly was then removed from the cryostat, and separate leak tests were performed on the cryostat and the bellows assembly. Both the cryostat and the bellows were found to leak. The bellows leak was relatively small, $\sim 2 \times 10^{-5}$ Scc He/sec, but significantly greater than the maximum allowable value specified by NASA; i.e., 10^{-6} Scc He/sec. Consequently, the bellows had already failed (using the definition of failure as leakage in excess of 10^{-6} Scc He/sec), and was not suitable for use in the cycle tests. It was concluded, however, that the bellows would be suitable for conducting cryogenic checkouts of the test apparatus, so it was not removed from the assembly at this time. Upon completion of the checkouts, it was planned to replace the bellows with the spare one, and then proceed with the 100 cycle test program in LH_2. The defective bellows could then be examined and repaired (if feasible) at leisure.

The cryostat leakage was found to be in the vacuum jacket, not in the lid or the lid/cryostat joint as had been suspected. The lead seal that joined the inner and outer vessels and functioned as the top sealing surface of the cryostat had failed. The cryostat had been used successfully in a number of different programs over a period of nearly ten years, but apparently was not designed to be pressurized as it was in this program. It was concluded that ultimately the lead seal would have to be replaced, but in order to avoid excessive delays in the bellows test program, a temporary repair was attempted with epoxy cement.

Cycle Test Procedure - The general procedure that was followed for the cycle tests is presented in the following paragraphs. This procedure is strictly applicable only to the cycle tests conducted with LH_2. A somewhat simplified procedure was employed for the LN_2 checkouts which were more easily conducted because of the elimination of hazards associated with the use of LH_2.

First, the entire system was purged with nitrogen gas using a "sweep purge" technique. Simultaneously the bellows was exercised (pressurized and then vented) several times to purge the air from the bellows and the pressurization gas storage vessel, and the bellows was left pressurized to $\sim$10 psig (150 kilo-newtons/meter^2) with helium. Subsequently, a similar "sweep purge" was accomplished with hydrogen gas to eliminate the condensibles (nitrogen) from the system.

The liquid hydrogen dewar was then positioned in the test cell, the transfer line connected and purged, and the cryostat fill procedure started. Care was taken during the fill to maintain the cryostat at a pressure of 6 psig (41.3 kilo-newtons/meter^2) or less (the maximum allowable working pressure for the lid, and the maximum allowable Δp for the bellows in the extended position).

Once the cryostat was filled (as indicated by the level sensors) and thermal equilibrium attained, the first cycle test was initiated. The recorders were turned on, then the cryostat was pressurized by closing the cryostat vent valve and turning the ullage heater on to a power level of 200 watts. Simultaneously, the bellows vent valve was opened to vent the bellows to ambient pressure, thereby initiating the fill portion of the cycle. When the cryostat pressure reached $\sim$4 psig (109 kilo-newtons/meter^2) several minutes later, the heater was turned off and the cryostat pressure carefully monitored. By this time the bellows had been forced to its fully extended position, and continued pressurization assured that the hydrogen within the bellows was subcooled and therefore in the liquid phase.

The expulsion portion of the cycle was initiated by simultaneously opening the helium pressurization and cryostat vent valves. The helium pressure was automatically regulated to $\sim$20 psig (219 kilo-newtons/meter^2) to produce the desired outflow rate. The orifice upstream pressure gage was monitored until an abrupt decrease in pressure to ambient was observed, thereby indicating termination of outflow and completion of the cycle. The recorders were annotated, then the next cycle was initiated. Data obtained from a typical cycle is shown in Figure 10.

Upon completion of the final cycle of a series the hydrogen was back-transferred from the cryostat to the dewar, and the cryostat warm-up begun. The ullage heater was turned on to a level of 300 watts, and the bottom heater to 200 watts while hydrogen gas from the dewar ullage volume was purged through the cryostat. The bellows was exercised several times to eliminate any residual liquid entrained in the bellows convolutions. Once the cryostat temperature reached $\sim 150^{o}$R (83^{o}K), the hydrogen gas was secured, and nitrogen gas was used to continue to warm-up and to purge the system of hydrogen. The cryostat pressure was carefully monitored and not allowed to exceed 6 psig (125 kilo-newtons/meter^2). The bellows was also exercised several times during the nitrogen purge to expell residual hydrogen. After it was certain that no significant quantities of hydrogen remained in the system, the cryostat was finally vented to atmospheric pressure.

In preparation for a leak check, the cryostat was first evacuated by means of the KS-47 rough pump to a pressure of $\sim$200 microns (26.2 newtons/meter^2), and the then pumped down to a pressure level of $\sim$.1 microns (0.0133 newtons/meter^2) by means of the portable high vacuum unit. Finally, the system was opened to the leak detector, and a quantitative measure of the helium leak rate was obtained.

<u>Liquid Nitrogen Checkouts</u> - To verify the suitability of the test apparatus and associated operating procedures with minimum expenditure of effort and maximum safety, a liquid nitrogen test series was conducted prior to attempting a test with liquid hydrogen.

The first series of LN_2 tests comprised 10 cycles, employing the basic test procedure previously described. Some variations were used from cycle-to-cycle to establish the optimum sequence of valve operation relative to the application of heater power, but these variations did not have a significant effect on the primary test results.

An attempt to leak check the bellows assembly immediately following the initial 10 cycle tests in LN_2 was unsuccessful because of excessive leakage into the cryostat. The cryostat could not be evacuated to the level required for a measurement by the leak detector, i.e., 10^{-4} mm Hg (0.0133 newtons/meter^2). Consequently, the bellows assembly was removed from the cryostat, and a leak check was performed by connecting the leak detector directly to the outlet connection on the bellows assembly. A leak rate of 2×10^{-5} Scc He/sec was measured, the same value as that obtained prior to the LN_2 checkout. To pinpoint the location of the leak, the inner bellows was removed from the assembly, connected to the leak detector, and carefully probed with a small helium gas probe while using Duxseal to isolate different regions of possible leakage. The general region of the failure was found to be in the bellows convolutions at the end nearest the outlet dome as shown in Figure 11. The leak definitely was not through the major welds of the assembly; consequently, repair by MMC was not possible. On the other hand, the leak was so small that it did not preclude use of the bellows for further checkout tests.

The spare bellows was also subjected to a leak check at this time to determine its condition. It was found to have a leak rate of only 6×10^{-10} Scc He/sec, a value several orders of magnitude less than the maximum allowable value.

Inspection of the cryostat revealed that there was still excessive leakage into the vacuum jacket. The repair previously attempted with epoxy had not been successful. Because of the hazards associated with the use of hydrogen in a cryostat with a leaky jacket, it was decided to defer further testing until a permanent repair could be effected. The cryostat was then removed from the system, and a new stainless steel face was fabricated and welded to the inner and outer shells to replace the lead seal as previously described.

Upon completion of the cryostat repair approximately two weeks later, a second series of 10 cycles in LN_2 was performed following the same basic procedure as used previously. The cryostat was left over night without draining the LN_2, and the liquid level the following morning indicated that the cryostat repair was successful. The heat leak into the cryostat was extremely small.

<u>Liquid Hydrogen Checkouts</u> - Following the LN_2 checkouts, the apparatus was prepared for cycle tests in LH_2, still using the original bellows. On 7 October a series of 5 cycles was successfully conducted, again using the same basic procedures previously described. Following backtransfer of the LH_2 into

the dewar and warmup of the cryostat, a leak check was attempted, but the pumpdown was exceedingly slow. As previously noted, it was speculated that the difficulty experienced in evacuating the cryostat was the result of condensation inside the pressurization gas storage vessel. The difficulty was overcome by a simple modification of the line connected to the storage vessel.

CYCLE TESTS WITH LIQUID HYDROGEN

Upon completion of the checkout tests and modifications noted above, the spare bellows was installed in the assembly in place of the original bellows, and final preparations were made for the first series of LH_2 cycle tests. A leak check of the complete system prior to cooldown revealed a leak rate of only 4×10^{-7} Scc He/sec, a value well within the required range.

The first series of 10 cycles with LH_2 was successfully conducted on 9 October. To conserve helium, the bellows was pressurized to only 20 psia (137.8 kilo-newtons/meter^2), resulting in an LH_2 expulsion rate of ~3 gpm (33×10^{-6} meters^3/sec) instead of the 5 gpm (56×10^{-6} meters^3/sec) originally planned. This change in the test conditions, however, did not compromise the basic objectives of the test in any way. Pertinent events and recorded data for a typical cycle are shown in Figure 10.

A leak check was successfully performed at the end of this first series of cycles with 5 psig (116 kilo-newtons/meter^2) Helium pressure on the bellows, but the leakage rate was determined to be 5×10^{-6} Scc He/sec, a value considerably greater than the 10^{-6} Scc He/sec allowed. It was reasoned, however, that some of this leakage was probably from sources other than the bellows itself, so the tests were not terminated at this point.

Two additional series of tests with LH_2 (10 cycles each) were conducted on 10 October. Leakages measured following each series were 7×10^{-6} 2×10^{-5} Scc He/sec, respectively, indicating no major change in leak rate throughout the 30 cycles. Subsequently, the LH_2 was back-transferred from the cryostat to the storage dewar, and the apparatus was warmed up overnight. A leak check performed on the bellows assembly alone after removal from the cryostat resulted in a value of 1.5×10^{-8} Scc He/sec. This confirmed the suspicion that a significant portion of the leakage measured with the bellows assembly installed in the cryostat occurs in the plumbing attached to the cryostat, and not in the bellows assembly. The leak rate was significantly greater than that measured previously for the inner bellows alone (6×10^{-10} Scc He/sec), but was still significantly less than the maximum allowable value.

The test apparatus was reassembled and two additional series of cycles were conducted a few days later. Upon completion of the first series (a total of 40 cycles) the leak rate measured with the bellows inside the cryostat was 1.5×10^{-5} Scc He/sec, essentially the same as previously (with the bellows installed in the cryostat). At the end of the second series (a total of 50 cycles) however, the leak rate had increased considerably and was "off-scale" for the CEC leak detector; i.e., $>10^{-4}$ Scc He/sec.

Subsequently the bellows was removed from the cryostat and leak checked. This time the leak rate was found to be 10^{-5} Scc He/sec for the bellows alone, one order of magnitude greater than the allowable value, and approximately 3 orders of magnitude greater than the rate measured at the end of 30 cycles. To be absolutely certain that this measurement was valid, it was double-checked by two different leak detectors. One of these, another CEC Model 24-120A detector, verified the value of 10^{-5} Scc He/sec; the other, a Veeco Model MS-12 leak detector simply gave an "off-scale" reading; i.e., $>10^{-6}$ Scc He/sec.

Further leak checking of the bellows following its removal from the assembly, revealed that this leak is also in the convolutions of the bellows, not other welds of the assembly. Therefore, as in the case of the original bellows, the leak is not reparable by MMC. At this point, the contractual requirements of the cycle test program had been satisfied, and testing was terminated.

Subsequently a supplemental agreement was negotiated whereby MMC agreed to conduct an additional 20 cycle tests. In accordance with this agreement, the spare bellows was subjected to an additional 20 cycle tests with LH_2 on 12 November. These tests were conducted with the same apparatus and in the same manner as the previous tests except that the instrumentation had been modified slightly, and only one leak check was conducted (at the end of the 20 cycles.) The instrumentation modifications consisted of the installation of lower range pressure transducers to provide more accurate readout at the relatively low pressure levels at which the cycle tests were conducted (see Table II).

Following the 20 cycle tests, the apparatus was warmed up and the bellows assembly was removed and subjected to a leak check. The leak rate was found to be exactly the same as before the 20 cycles; i.e., 10^{-5} Scc He/sec. Hence the failure had not progressed at all as a result of the last 20 cycles.

Upon completion of the cycle tests, the spare bellows was removed from the assembly and packaged for shipment to SOLAR. On 9 December, the LeRC Project Manager visited MMC to review final test results, and hand-carried both bellows to SOLAR for failure analysis. Results of this analysis are included in the following section of this report.

CYCLE TEST RESULTS

Although the operational life that was obtained from the cryogenic bellows did not meet expectations, it is probably more than adequate for many of the bellows applications that may be cited. It had been anticipated that the bellows would not fail (develop a leak exceeding 10^{-6} Scc He/sec) as a result of 100 complete cycles in liquid hydrogen, but that did not prove to be the case. Instead, the bellows originally installed in the assembly was found to have failed before the cycle tests were initiated, and the spare bellows subsequently failed prior to the completion of 50 cycles in LH_2.

The leak rate that was measured for the original bellows upon completion of 10 cycles in LN_2 was 2×10^{-5} Scc He/sec. This is more than a full order of magnitude greater than the maximum allowable leakage, but it still constitutes a very small leak. Even at this leak rate, more than 12 hours (43.2×10^3 sec) would be required for 1 cc (10^{-6} meters^3) of helium to leak through the bellows.

In developing a leak of this magnitude, the bellows had been subjected to ~50 cycles; i.e., 10 cycles in water, and 10 in LN_2 at SOLAR, plus 13 cycles in expulsion efficiency tests, 10 in LN_2, and at least 6 during purging operations at MMC. Similarly, the spare bellows failed prior to the completion of 50 cycles. It had developed a small leak during the first 30 cycles in LH_2 that increased to an unacceptable level (10^{-5} Scc He/sec) at the end of 50 cycles. An additional 20 cycles, however, did not result in a further progression of the failure. Undoubtedly there are many applications that would not subject the bellows to this number of cycles, and consequently could utilize the existing bellows design without modification.

In order to pinpoint the cause of the failures, both bellows assemblies were cut open by SOLAR so that an internal inspection could be performed. Two leak areas on the original bellows were traced to corrosion (rust colored) spots under the lip where the .006 inch (0.000153 meters) thick bellows sleeve is joined to the .025 inch (0.000635 meters) thick support ring. The single leak area on the spare bellows was traced to a similar corrosion spot at the root of the first convolution from the support ring.

To further investigate the nature of the failure, a section approximately 3" wide was cut out of the original bellows as shown in Figure 12 and the cut-out section was expanded so that it could be subjected to a more detailed inspection. Additional corrosion spots were observed as shown in Figure 13. These spots are presumed to be caused by foreign particles in contact with moisture, but the exact source of these contaminants is only speculative. The bellows were dried for several hours at 200°F (366°K) following the water cycle tests at SOLAR, but the tap water that had been used may have left undesirable contaminants. In the future it is proposed to use deionized water instead of tap water.

CONCLUSIONS AND RECOMMENDATIONS

The expulsion efficiency of the bellows assembly was found to be approximately 98.5%, a value comparable to that attainable with other types of positive expulsion devices (bladders and diaphragms). Consequently, this particular design of bellows has no shortcomings in this regard.

Although the bellows did not achieve the cycle life expected, the failures that did occur after 50 cycles were minor; i.e., total leak rate was only 10^{-5} Scc He/sec. With only two samples to provide data, it is difficult to draw firm conclusions, but there is no positive evidence that the LH_2 environment was a factor in the failures. Both bellows failed in the same manner prior to the completion of 50 cycles, but one of the bellows was not tested in LH_2 at all, while the other was tested only in LH_2.

The basic design employed for the bellows appears to be satisfactory, in fact there may be many applications in which the bellows could be employed successfully without modification. A redesign of the weld joint between the bellows sleeve and the support ring does appear to be in order. In particular, a butt weld is recommended so that the crevice formed by the bellows sleeve and the end domes in the current design will be eliminated.

It is also recommended that more thorough cleaning of the bellows be accomplished following fabrication, preferably attaining a cleanliness level equivalent to that required for LOX service in accordance with NASA MSFC Specification 164. Also, greater care should be exercised to exclude contaminants from the bellows after cleaning. Specifically, the practice of using tap water in the bellows should be discarded in favor of deionized water, and subsequent drying should be accomplished at a temperature and duration that positively assures the elimination of all moisture.

TABLE I

EXPULSION EFFICIENCY TEST DATA

Test No.	Volume of Water, ml (Meters³) Added	Expelled	Difference	No. of Cycles	Efficiency %
1	11,813 (0.011813)	11,744 (0.011744)	69 (0.000069)	1	99.4
2	11,795 (0.011795)	11,698 (0.011698)	97 (0.000097)	1	99.2
3	11,795 (0.011795)	11,610 (0.011610)	185 (0.000185)	5	98.4
4	11,816 (0.011816)	11,628 (0.011628)	188 (0.000188)	6	98.4

TABLE II - BELLOWS INSTRUMENTATION

Data Point	Measurement	Operating Range	Transducer	Readout	System Accuracy
1	Orifice Upstream Pressure	0 to 50 psia* (0 to 345 KN/m^2)**	CEC* 4-326	Bristol Recorder	± 1%
		0 to 25 psia (0 to 172 N/m^2)	CEC 4-312		
2	Cryostat Pressure	0 to 50 psia* (0 to 172 N/m^2)	Teledyne* 185	Bristol Recorder	± 1%
		0 to 25 psia (0 to 172 N/m^2)	CEC 4-312		
3	Bellows Pressure	0 to 50 psia (0 to 345 N/m^2)	Teledyne 185	Bristol Recorder	± 1%
4	Cryostat Inlet Temperature (Helium Gas)	75 to 300°K	CU/CON	Bristol Recorder	± 3.6°K
5	Bellows Inlet Temperature (Helium Gas)	75 to 300°K	CU/CON	Bristol Recorder	± 3.6°K
6	Cryostat Temperature	19 to 30°K	Platinum	Bristol Recorder	± 0.055°K
7	Liquid Level (High)	On-Off	Carbon	Lights	--
8	Liquid Level (Low)	On-Off	Carbon	Lights	--
9	Ullage Heater	0 to 800 Watts		Meter	--
10	Bottom Heater	0 to 200 Watts		Meter	--

* High range transducer installed initially; later replaced with lower range transducer

** Kilo-Newtons/meter^2

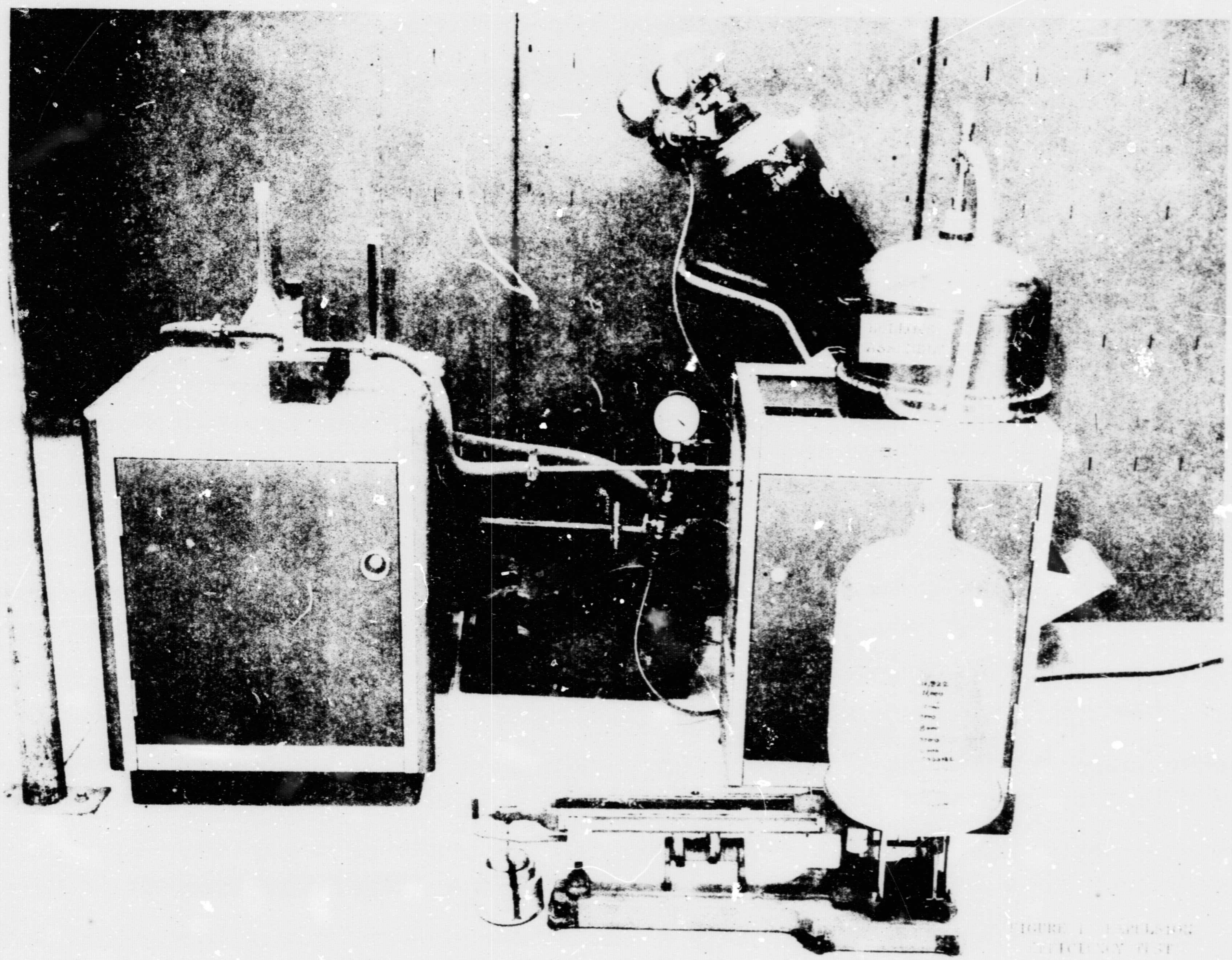
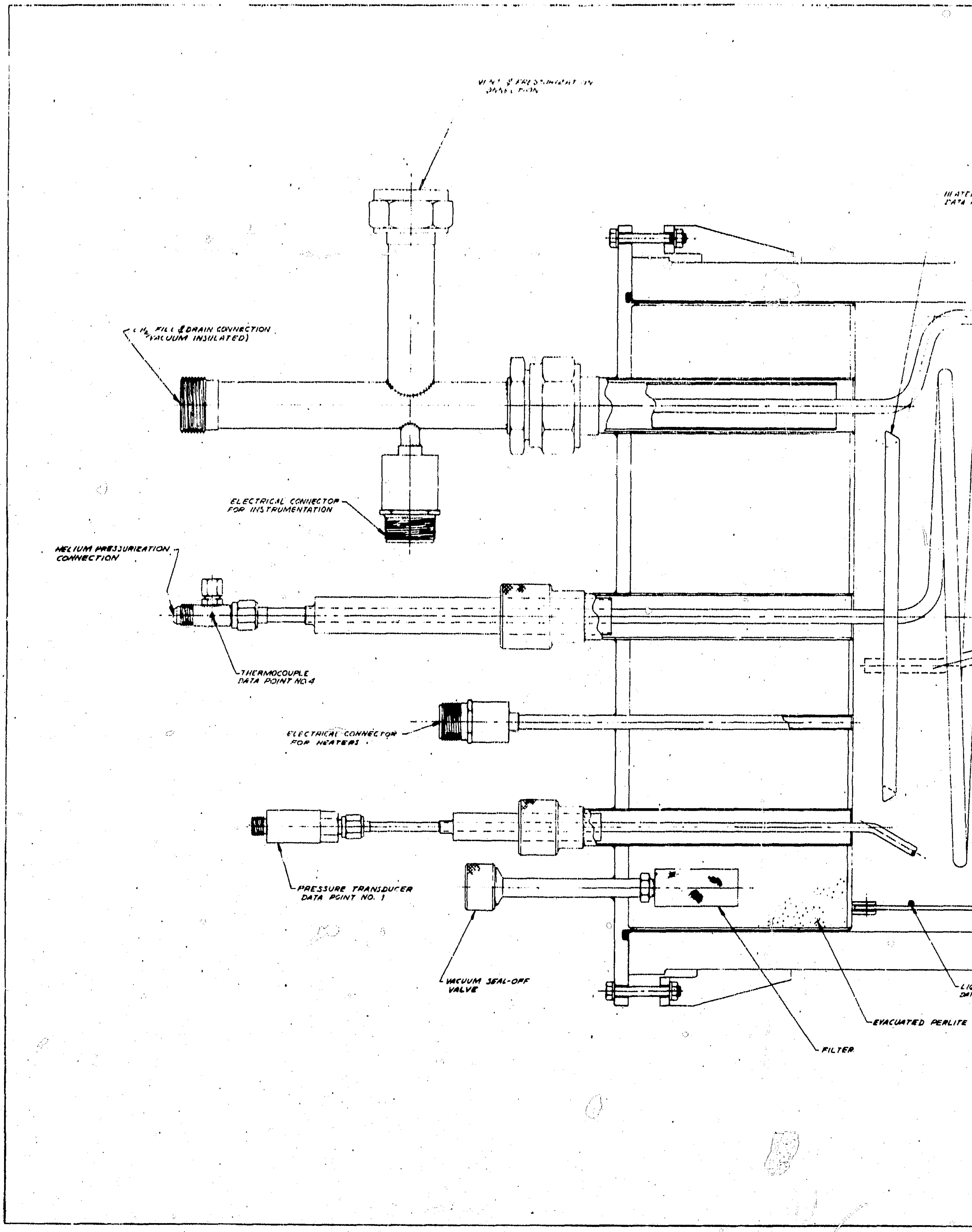
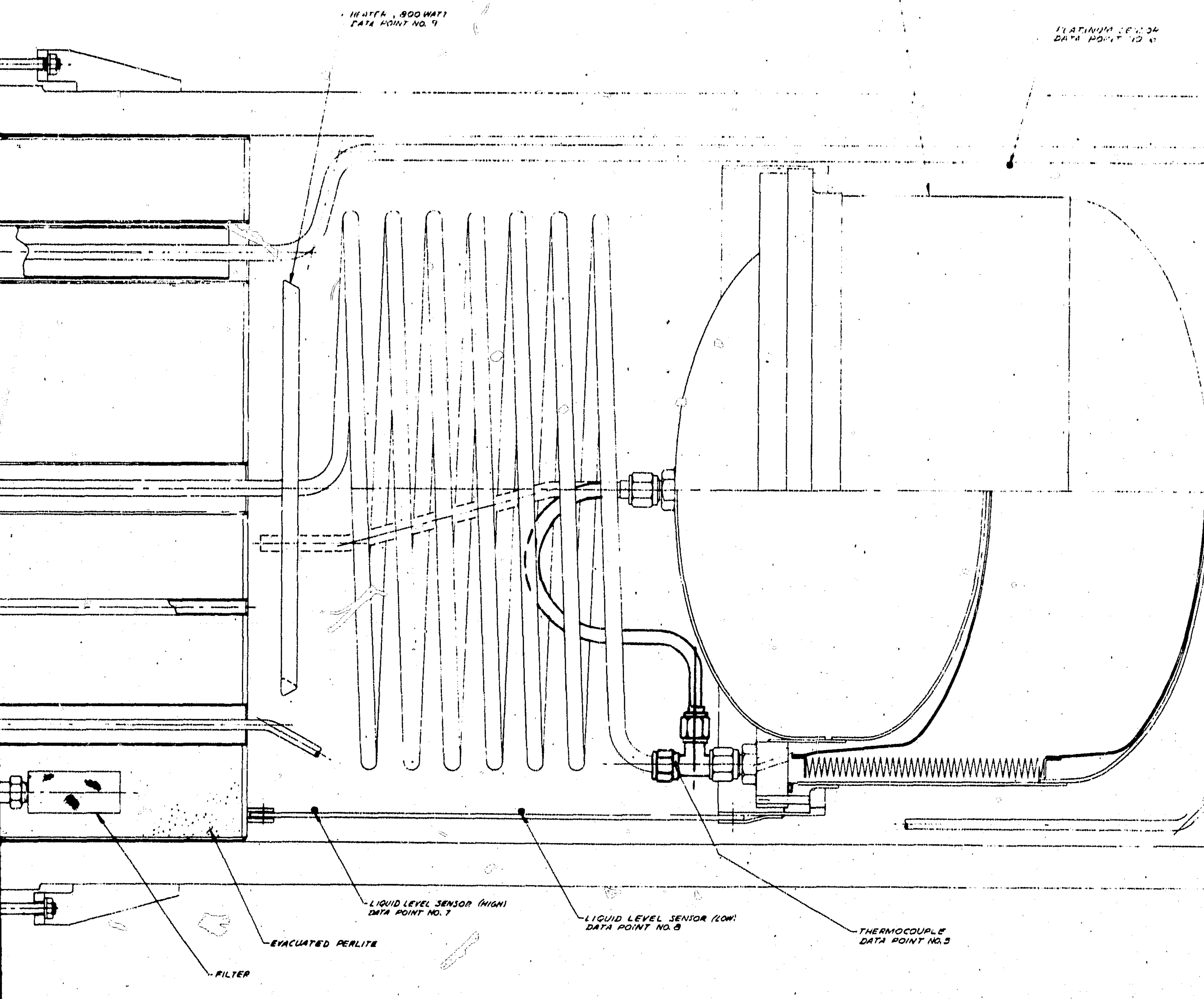


FIGURE 1. DISPERSION EFFICIENCY TEST APPARATUS


LH_2 FILL & DRAIN CONNECTION (VACUUM INSULATED)
ELECTRICAL CONNECTOR FOR INSTRUMENTATION
HELIUM PRESSURIZATION CONNECTION
THERMOCOUPLE DATA POINT NO. 4
ELECTRICAL CONNECTOR FOR HEATERS
PRESSURE TRANSDUCER DATA POINT NO. 1
VACUUM SEAL-OFF VALVE
EVACUATED PERLITE
FILTER

20H


HEATER, 800 WATT
DATA POINT NO. 9
LIQUID LEVEL SENSOR (HIGH)
DATA POINT NO. 7
LIQUID LEVEL SENSOR (LOW)
DATA POINT NO. 8
THERMOCOUPLE
DATA POINT NO. 5
EVACUATED PERLITE
FILTER

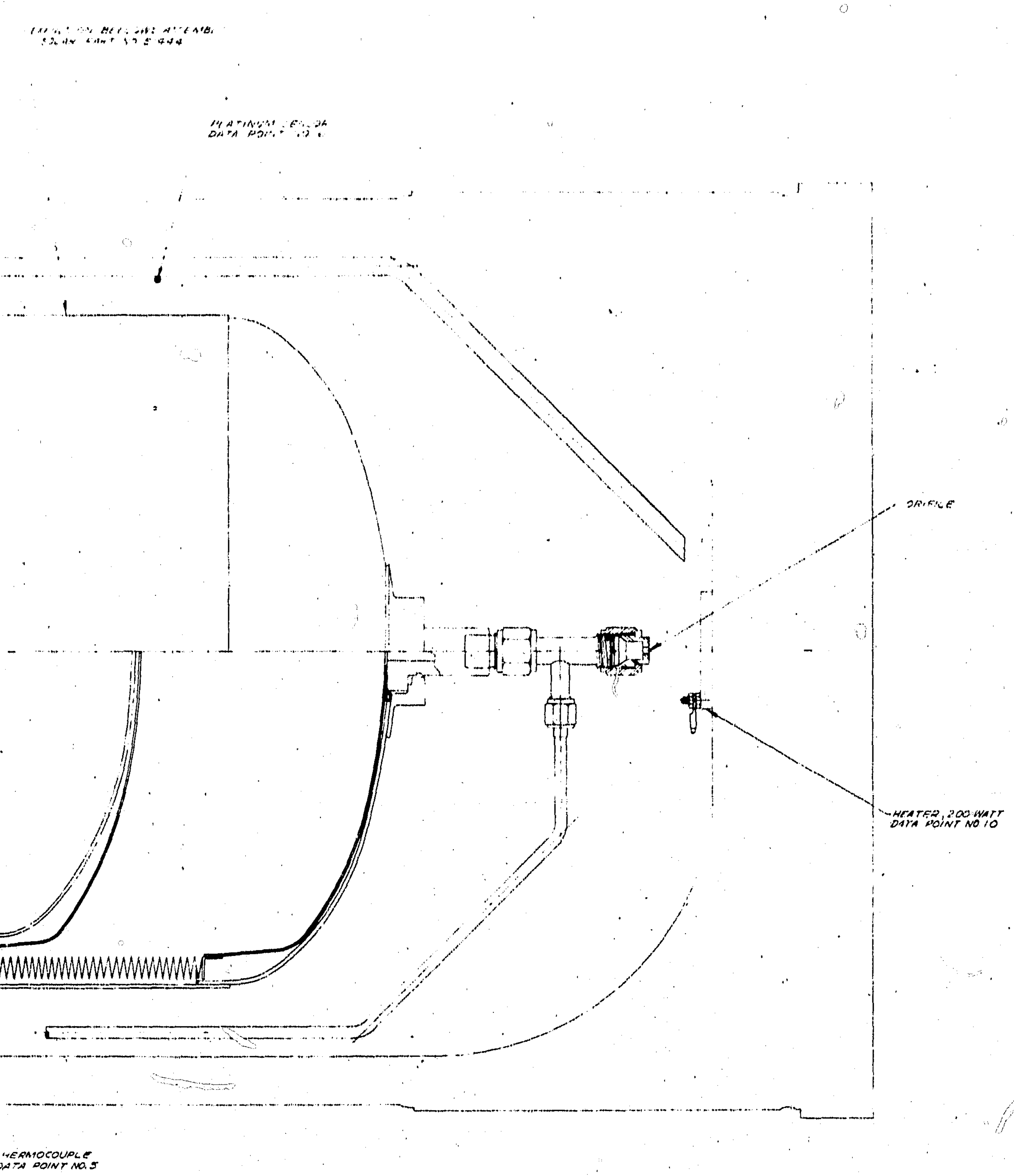


FIGURE 2 - LAYOUT OF
CRYOSTAT ASSEMBLY

FIGURE 3 - INNER BELLOWS SECTION

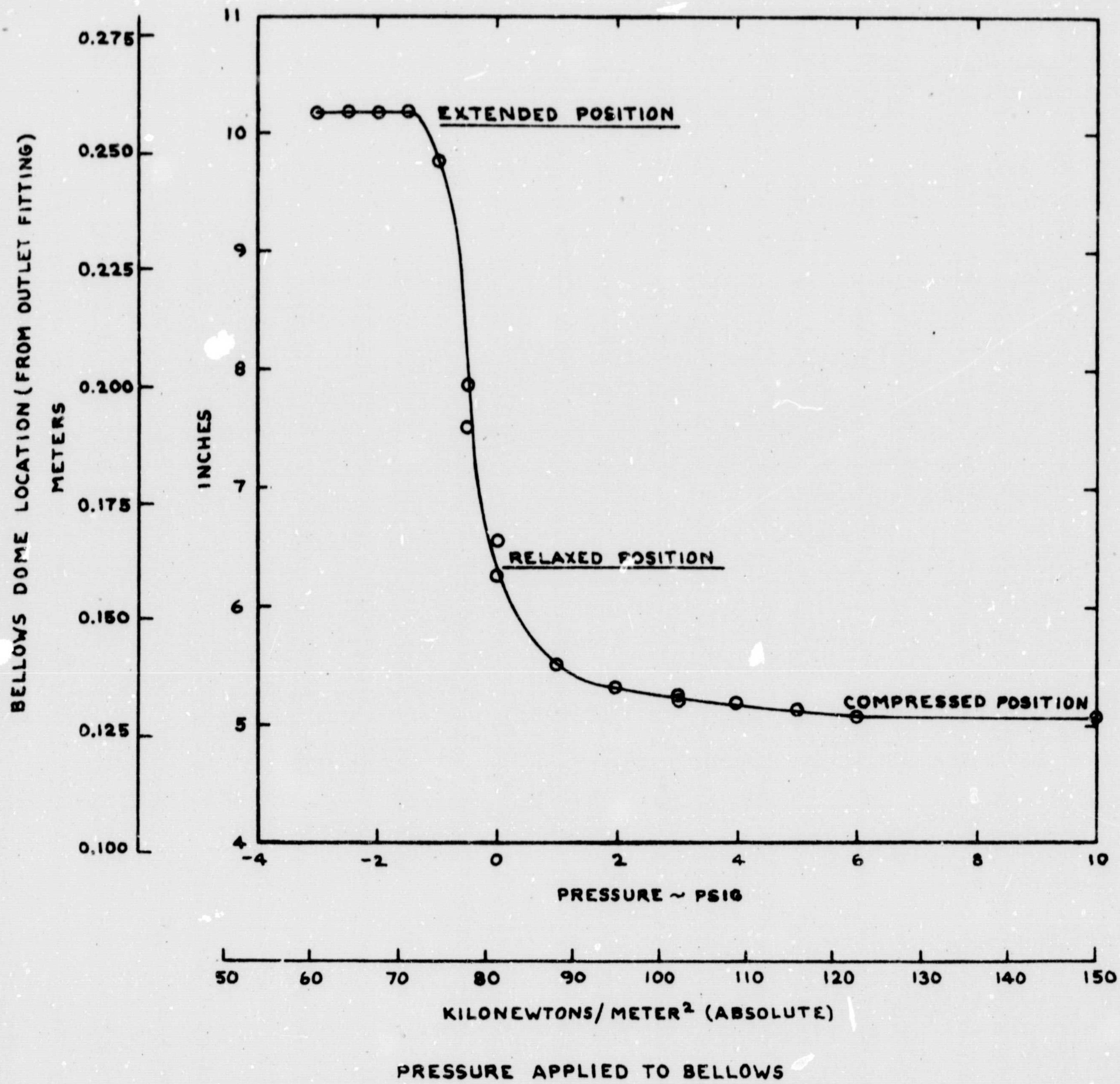


FIGURE 4 — BELLOWS DEFLECTION VS. PRESSURE

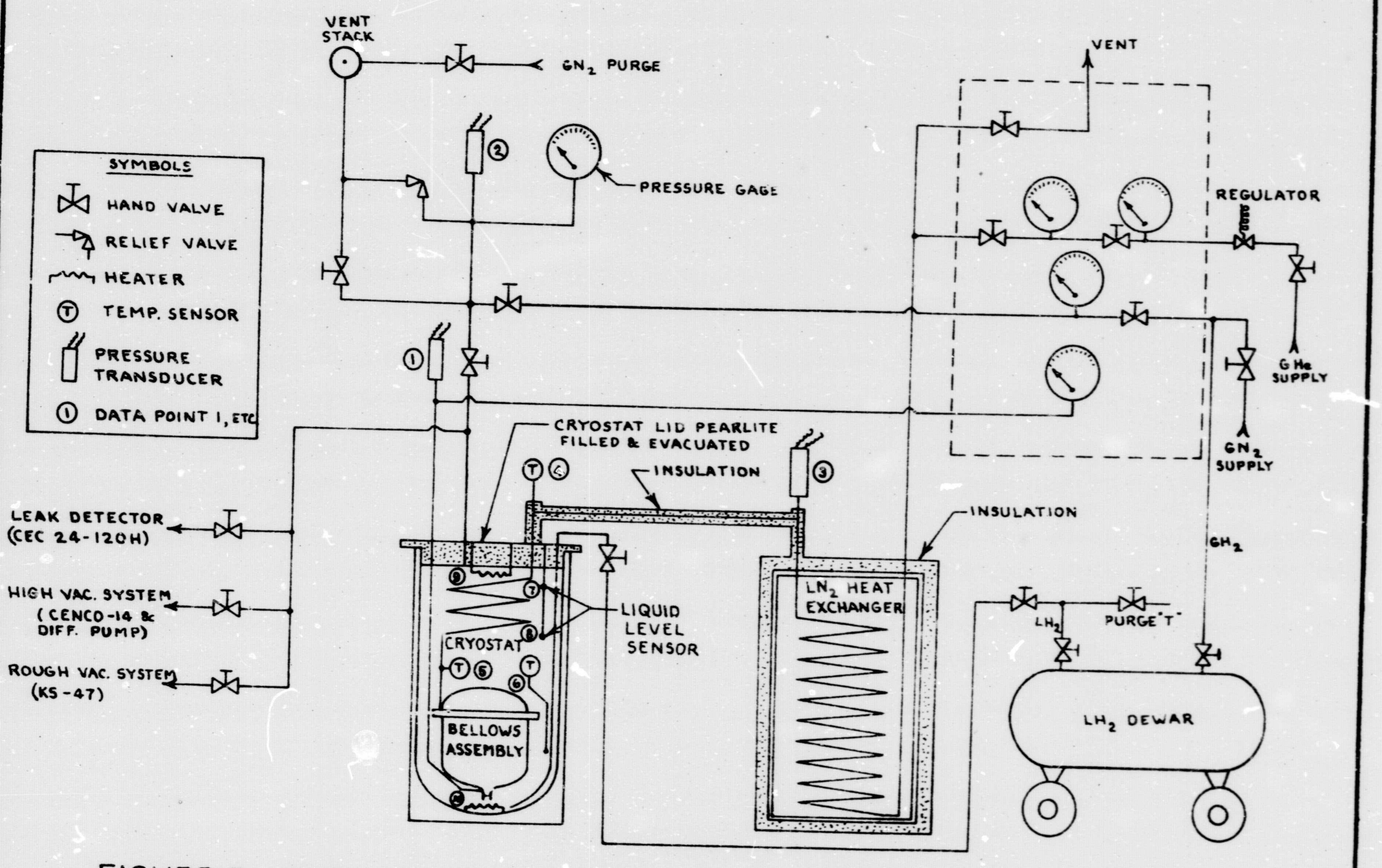


FIGURE 5 - EXPULSION BELLOWS TEST SCHEMATIC

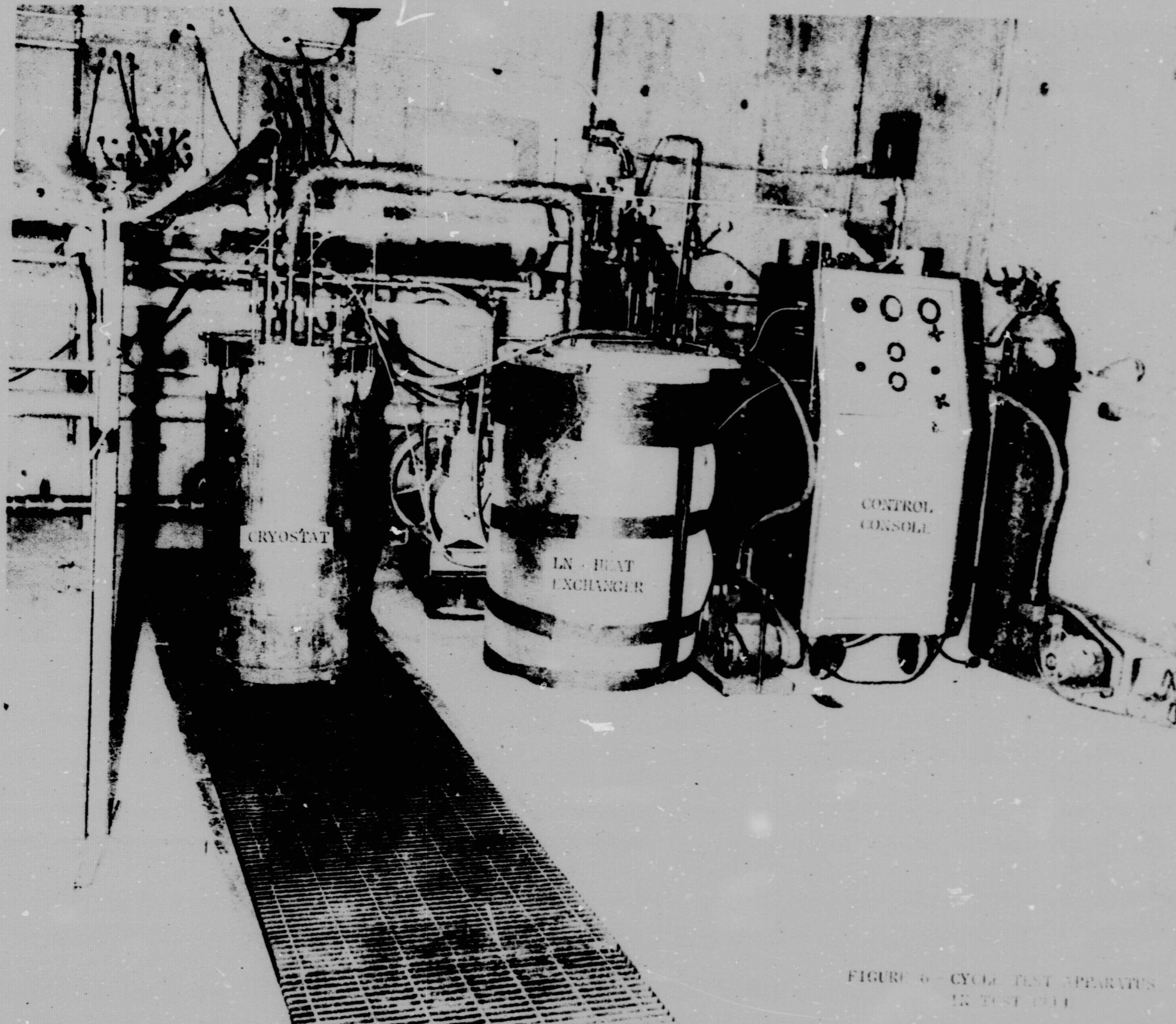


FIGURE 6 - CYCLE TEST APPARATUS IN TEST CELL

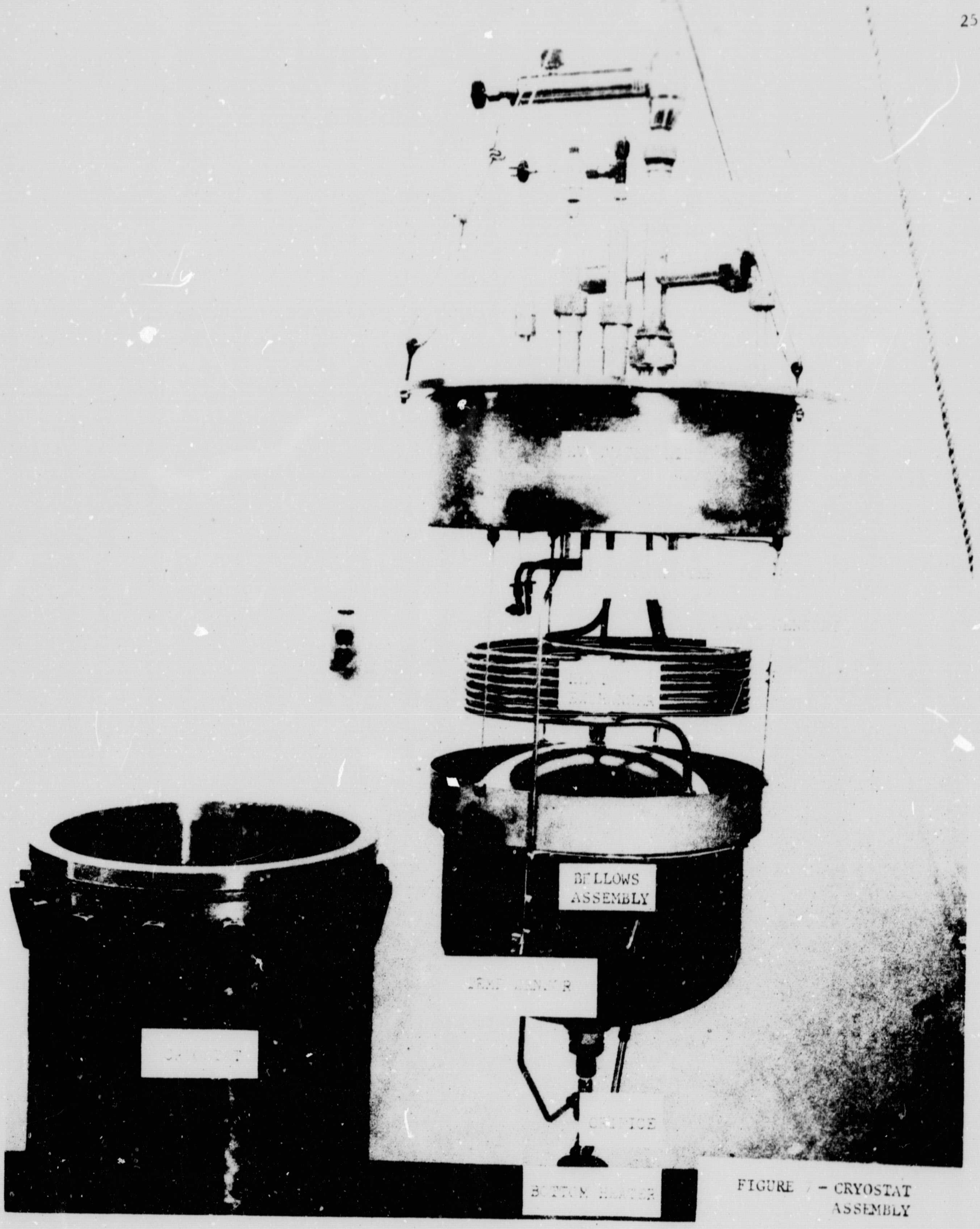


FIGURE [illegible] - CRYOSTAT
ASSEMBLY

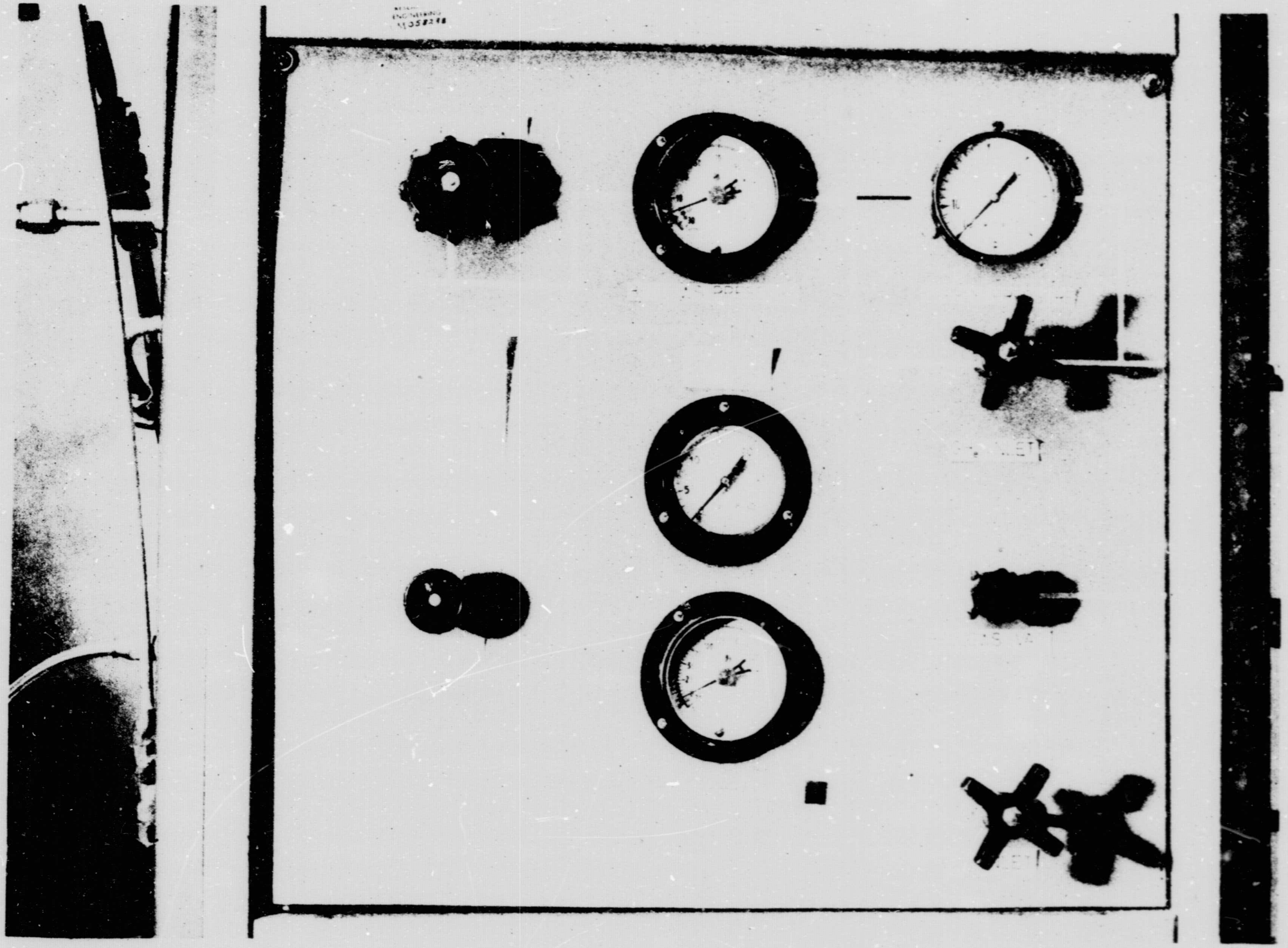


FIGURE 8 - CONTROL PANEL

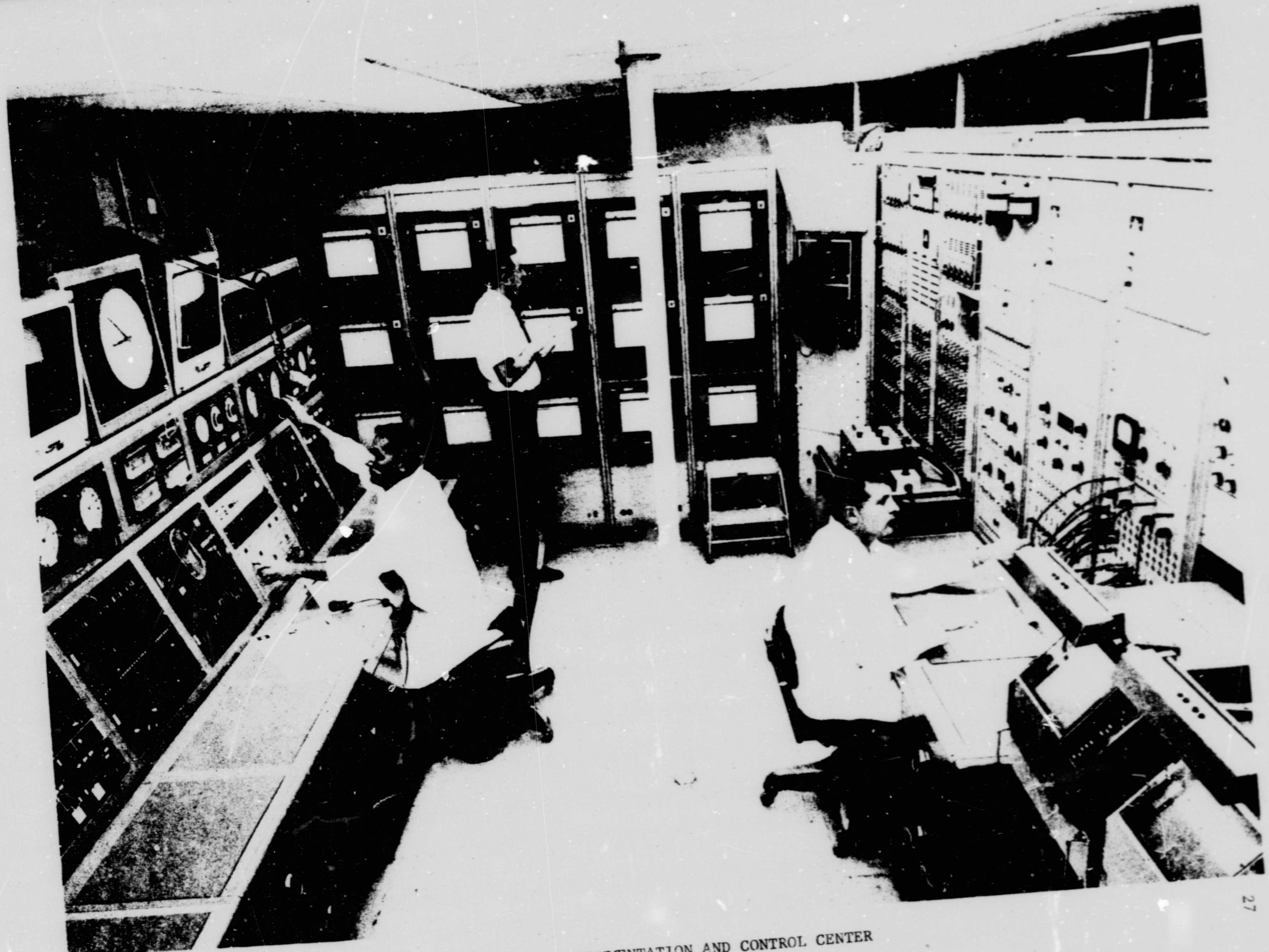


FIGURE 9 - INSTRUMENTATION AND CONTROL CENTER

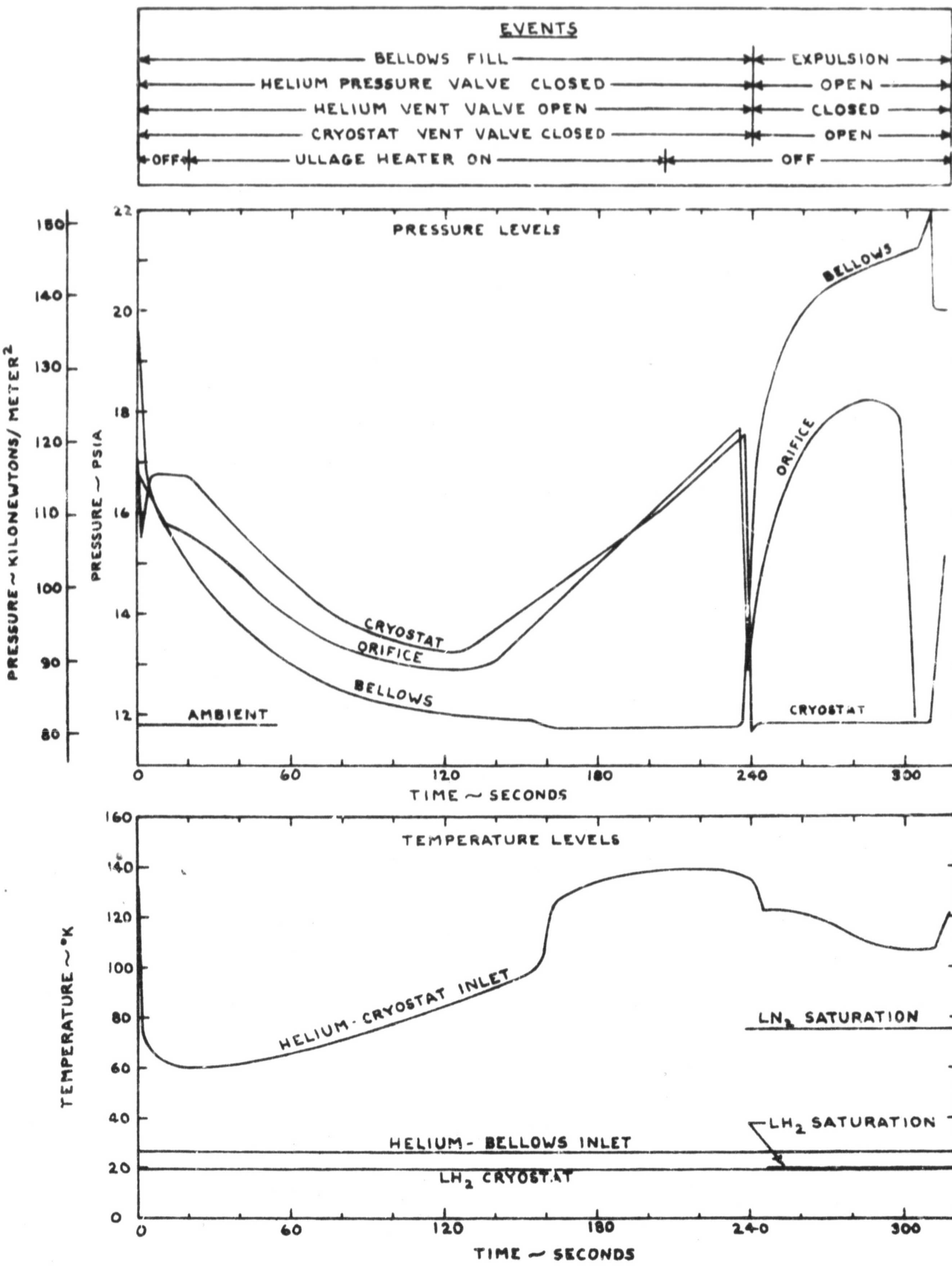


FIGURE 10 — TYPICAL CYCLE TEST DATA

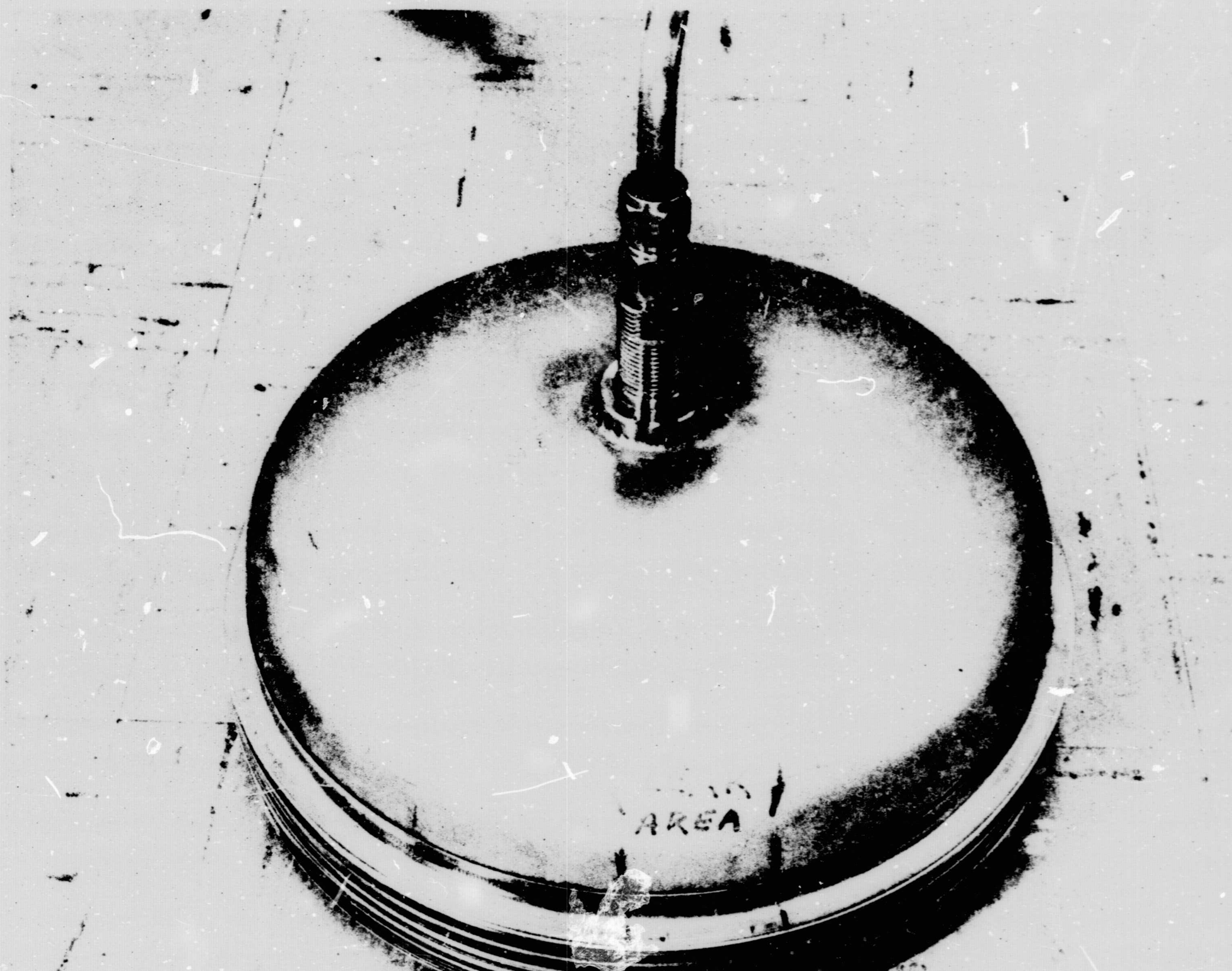


FIGURE 11. [illegible]
[illegible]

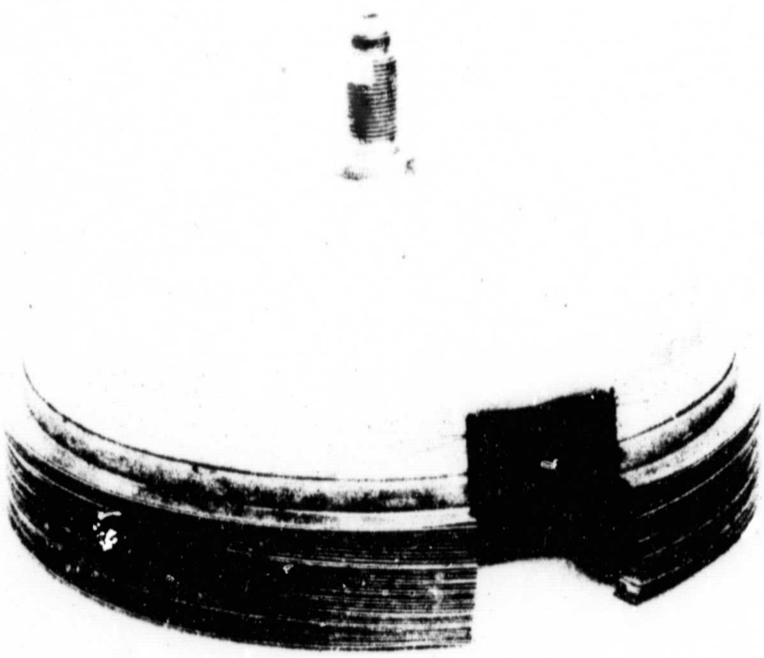


FIGURE 12 - SECTIONED BELLOWS

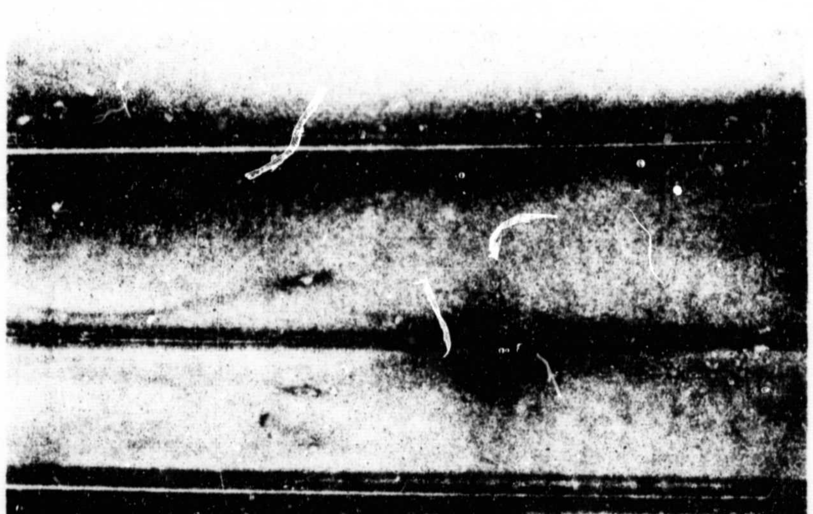


FIGURE 13

CORROSION SPOTS ON BELLOWS INNER SURFACE

APPENDIX A

INSTRUMENTATION CALIBRATION PROCEDURES

Pressure Measurements

1. Install the pressure transducer on the facility gaseous nitrogen calibration console. This consists of several high accuracy test gauges.

2. Connect the pressure transducer electrically to the bridge balance and power supply unit and the recorder channel selected for obtaining the test data.

3. Adjust the power supply voltage to the value recommended by the pressure transducer manufacturer.

4. Adjust the bridge balance potentiometer for a zero millivolt output of the transducer at 0 psig (102 kilo-newtons/meter^2, absolute).

5. Adjust the recorder zero for the desired rest position.

6. Adjust the gaseous nitrogen calibration source for the desired maximum psig of the transducer.

7. Adjust the recorder span for the desired deflection position.

8. Repeat steps 4 through 7 until no change is noted in either the zero or maximum recorder positions.

9. Record the zero, maximum, and 4 other psig steps of the transducer to determine its calibration and resulting accuracy.

10. Record the shunt calibration steps of 20K, 40K, 80K, 160K and 320K ohms for the purpose of respan and drift checks.

Temperature Measurements (Platinum Bulbs)

A certified calibration, traceable to the National Bureau of Standards, is furnished with each platinum resistance sensor by the supplier (Rosemount Engineering Company). The sensors are used in conjunction with a Triple-Bridge Multi-Channel electronic device. The specific calibration procedure employed is as follows:

1. After the power to the chassis has been on for approximately 30 minutes (1800 seconds), each individual power supply must be adjusted to 30 volts. The adjustment may be accomplished with a

millivoltmeter of 0.02% accuracy or better connected to the phone jack of each channel on the front panel. Then depress the calibrate switch to "CAL" and turn the screwdriver adjustment immediately above the phone jack until the millivoltmeter reads 20,000 millivolts.

2. Set the decade box to the resistance value corresponding to the null or zero point given on the data sheet supplied with the temperature sensor being calibrated.

3. The system is ready to operate upon completion of the installation and calibration of the TBU's. Be certain that the temperature sensor and readout equipment are connected to the proper channels.

4. Energize the 0% or zero calibrate circuit by means of the appropriate remote control or front panel simultaneous switch. All channels will provide zero millivolts output. Any one channel may be 0% calibrated by energizing the front panel individual switch to provide a zero millivolt output. Adjust the zero adjust if necessary on the readout equipment on each channel to its true zero position.

5. Energize the 100% or full scale calibrate circuit by means of the appropriate remote control or front panel simultaneous switch. All channels will provide 10 millivolt output. Any one channel may be 100% calibrated by energizing the front panel individual switch to provide a 10 millivolt output. Adjust the gain control if necessary on the readout equipment on each channel for full scale reading.

6. The system is ready to measure and record upon completion of the last step.

Temperature Measurements (Thermocouples)

All thermocouple wire purchased by MMC is of premium grade and conforms to the standards of the Instrument Society of America. Each lot of wire is checked by the MMC Metrology Laboratory before use to verify its calibration with the NBS calibration tables.

Each thermocouple output is fed back to the Instrumentation and Control Center through thermocouple extension cable, and connected to an electronic reference unit that maintains a stable reference temperature to within $\pm$ .05°K. The resultant signal is then recorded on an adjustable span stripchart recorder. The recorders are checked twice a year to assure that the power supply and adjustment pots are functioning properly. Adjustment of the recorder is accomplished as follows:

1. Connect a millivolt potentiometer to the input of Bristol Strip Chart recorder selected for temperature readout.

2. From the NBS thermocouple temperature versus emf calibration table, select the voltage corresponding to the minimum temperature to be recorded and apply this voltage to the recorder.

3. Adjust the recorder to the zero position on the chart paper.

4. From the calibration table select the voltage corresponding to the maximum temperature to be recorded and apply this voltage to the recorder.

5. Adjust the recorder span for the desired deflected position.

6. Repeat steps 2 through 5 until no further adjustment is required.

7. Install a thermocouple scale on the recorder corresponding to type of thermocouple wire used and the temperature range to be recorded.

8. Disconnect the millivolt potentiometer from the circuit and connect the thermocouple in its place.